# A THz Gyrotron FU CW III with a 20T superconducting magnet

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A gyrotron with a 21.4 T pulse magnet has achieved the first experiment on a breakthrough of 1 THz. On the basis of the success, the latest gyrotron FU CW III was designed and constructed. The gyrotron included Gyrotron FU Series, is introduced in detail. It consists of a 20T superconducting magnet, a demountable gyrotron tube, a 30 kV, 0.5 A, CW power supply for electron gun and additional coils in a gun region. The gyrotron has achieved frequency step tuneability up to around 540 GHz for fundamental operations and up to 1.08 THz for second harmonic operations.

Keywords: Gyrotron, High power THz source, Terahertz, CW operation, DNP-NMR, Superconducting magnet,

## 1. Introduction

Recently, gyrotrons with high field pulse magnets[1),2)] have achieved a breakthrough of 1 THz. It is great success for gyrotrons to be included in THz radiation sources with an advantage of high power output 0.1 to 10 kW. Such high power THz radiation can be used for many applications to high power THz technologies, for example, NMR at 1GHz with Dinamic Nuclear Polarization (DNP)[3)], X-ray Detected Magnetic Resonance (XDMR) experiment with high power THz radiation, accurate measurement of energy level of positronium, etc. In such applications, pulse operations of THz gyrotrons are not enough. Now, FIR FU began to develop Gyrotron FU CW Series for high power THz technologies.

On the basis of the successful experiment on breakthrough of 1 THz by use of 21.4 T pulse magnet, a gyrotron FU CW III with a 20T superconducting magnet[4)] was designed for high frequency CW operations up to 1 THz by using second harmonics. It was already constructed and tested successfully. In this paper, the results of both gyrotrons are presented.

### 2 A THz gyrotron with a pulse magnet

A THz gyrotron consists of a gyrotron tube with high Q value for high frequency cavity modes, an ice-protecting pulse magnet whose maximum field intensity is around 21.4 T, 300 kJ capacitor bank for operating the pulse magnet, power supplies for a triode magnetron injection gun and gun coils and a controlling system for the whole gyrotron system. Fig. 1 shows the block diagram of the whole system of the THz gyrotron.

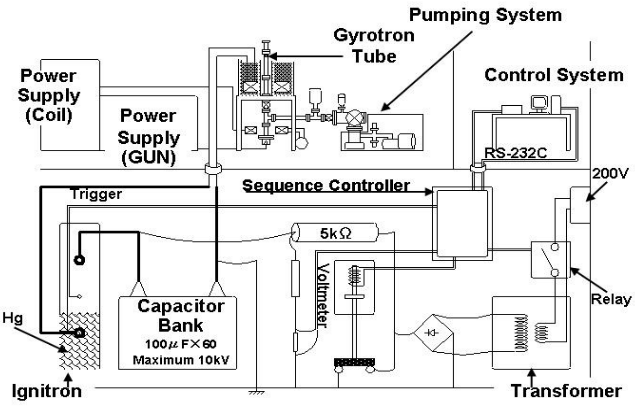


Fig. 1 The block diagram of the whole system of a THz gyrotron with a pulse magnet

An ice-protecting pulse magnet is installed on the second floor. It is a simple solenoid coil. Copper wire is wound in 299 turns. The inner diameter, outer diameter and length are 43 mm, 129.4 mm and 112 mm, respectively. The coil is inserted in stainless steel cylinder whose inner diameter and thickness are 170.3 mm and 22.4 mm, respectively. Water with alumina powder is surrounding the coil and fulfill the clearance between the coil and a stainless steel cylinder. The whole system of an ice-protecting pulse magnet is installed in a cryostat and cooled

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down by liquid nitrogen. Then, water with alumina powder is frozen and fixes the solenoid coil tightly in order to protect the coil from expanding in radial direction during pulse operation.

The pulse magnet is operated by use of a capacitor bank installed on the first floor. The total capacitance is 6 mF and maximum biased voltage is 10 kV. Therefore, the maximum stored energy is 300 kJ. It is discharged through an ignitron and applied to the pulse magnet. The field intensity is increased up to 21.4 T at the biased voltage of 5.7 kV and the pulse half-value width is typically, around 11 ms. The gyrotron operates in short pulse which is limited by a high voltage power supply. A typical pulse width of the output of the supply is 1 ms. The timing of the pulsed operation is controlled by the controlling system from the second floor. In addition to the pulse magnet, three pieces of water-cooled copper coils are installed in the gun region for controlling parameters of electron beam.

A demountable gyrotron tube is installed on the center axis of 21.4 T pulse magnet. In the operation test, a high voltage pulse is applied to electron gun at around the maximum field intensity $B_0$. When B is changed, many cavity modes are excited at the fundamental and second harmonic of cyclotron frequency. One of measurement results for operation of a THz gyrotron is demonstrated in Fig. 2. Radiation power detected by InSb cooled by liquid helium is traced as functions of magnetic field. Radiation power $P_{0.5}$ in the lower trace is detected after a high pass filter with a hole of 0.5 mm in diameter (the corresponding cutoff frequency $f_c$=351.6 GHz), while radiation power $P_{0.3}$ in the upper trace after a high pass filter with hole of 0.3 mm in diameter ($f_c$=586.0 GHz). The magnetic field intensity is varied from 14.5 T to 16.0 T in the time interval (1 ms) of the high voltage pulse applied to a gun cathode. During the interval, corresponding frequencies of fundamental and second harmonic operations vary from 383 GHz to 421 GHz and from 767 GHz to 841 GHz, respectively. Therefore, radiation power detected after 0.3 mm filter includes only second harmonic radiations, while radiation power detected after 0.5 mm filter both fundamental and second harmonic radiations. In the upper trace of Fig. 2, the magnetic field corresponding to the observed radiation peaks are 14.8 T and 14.9 T. Therefore, this means that the second harmonic operations occur at the frequencies of 783 GHz and 789 GHz, which are almost same as the frequency of $TE_{0,10}$ or $TE_{2,10}$ cavity mode. It is expected from the calculation results for starting current, that these mode has a possibility of mode competition with $TE_{4,4}$ or $TE_{2,5}$ fundamental cavity modes. In the lower trace, it seems that these fundamental modes or one of them are excited. Corresponding powers are observed in the magnetic field region from 14.8 to 15.0 T. Generally, the output powers of fundamental operations are much higher than those of the second harmonics. Therefore, the second harmonics are overlapped by the fundamentals and the radiation peaks do not appear there.

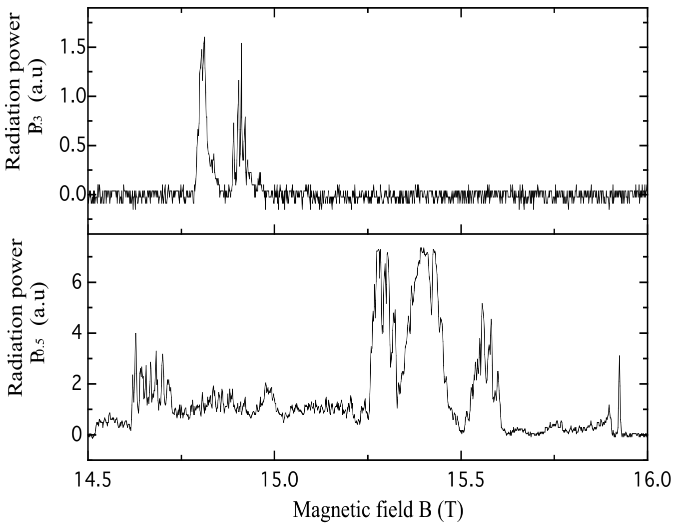


Fig. 2 Radiation power measured by use of an InSb detector cooled by liquid helium as magnetic field generated by a pulse magnet. Upper trace: Radiation power $P_{0.3}$ after a high pass filter with a hole of 0.3 mm in diameter which includes only second harmonic operations. Lower trace: Radiation power $P_{0.5}$ detected after a high pass filter with a hole of 0.5 mm in diameter which includes both the fundamental and the second harmonic operations.

Fig. 3 shows the result of a similar measurement where the field intensity is increased further. The radiation ($P_{0.3}$) pulse observed in the middle trace results from second harmonic operation, because it penetrates through a high-pass filter with a hole of 0.3 mm in diameter. The magnetic field corresponding to the observed radiation peak is 19.0 T. Therefore, the second harmonic operation occurs at the frequency of 1.005 THz which is almost same as the frequency of $TE_{6,11}$ cavity mode.

Similar measurements have been carried out in wide range of magnetic field intensity. In any cases, second harmonic operations were separated from the fundamental operations by using high pass filters. Many operation modes at the fundamental and the second harmonics were already found. The expected frequencies of observed radiation peaks estimated

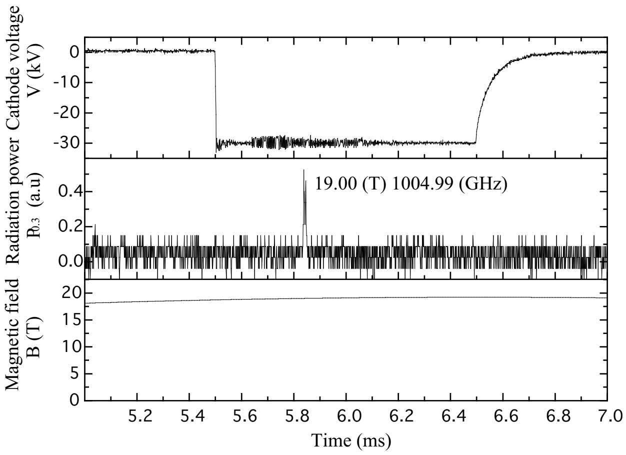


Fig. 3 Radiation power $P_{0.3}$ (middle trace) measured as a function of time by use of an InSb detector cooled by liquid helium with variation of magnetic field (lower trace) generated by a pulse magnet *B* and cathode voltage *V*(upper trace) . The radiation pulse observed in the middle trace results from second harmonic operation, which penetrates through a high pass filter with a hole of 0.3 mm in diameter.

from corresponding field intensities are plotted in Fig. 4 as functions of magnetic fields. Frequency step tuneability is achieved in the frequency ranges from 387 GHz to 471 GHz by fundamental operations and from 711 GHz to 1015 GHz by second harmonic operations. The highest frequency has achieved the breakthrough of 1 THz. This is the first experiment for a THz gyrotron using high magnetic field exceeding 19.1 T and second harmonic operation[1).]

**3 Gyrotron FU CW III**

For application of THz gyrotron, CW opration is much more convenient than pulse operation. We have developed two CW sub-THz gyrotrons named Gyrotron FU CW I and II. The third gyrotron of Gyrotron FU CW Series, Gyrotron FU CW III with a 20 T superconducting magnet has recently been constructed and operated. In Table 1, main parameters of the gyrotron are shown. The gyrotron is optimized for the second harmonic operation of $TE_{4,12}$ at the frequency of 1013.7 GHz. The operation mode is complete CW. This gyrotron has achieved the breakthrough of 1 THz in CW operation.

In addition, many other cavity modes were excited by adjusting the field intensity at the optimum value for each cavity mode. As the results, The gyrotron has achieved frequency step tuneability in wide range covering sub-THz to THz frequency region.

Fig. 5 shows a photo of Gyrotron FU CW III. The operation test has already been carried out successfully.

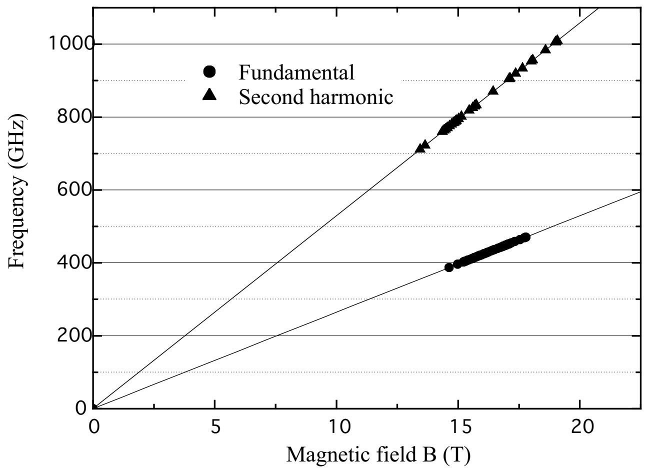


Fig. 4 Expected frequencies of observed radiation peaks at the fundamentals and the second harmonics as functions of magnetic fields *B*.

Table 1 Specification of Gyrotron FU CW III

| |
|---|
| Total height from electron gun to the window: 2.4 m |
| Superconducting magnet : |
| Maximum magnetic field : 20 T |
| Inner bore diameter: 50 mm |
| Cavity : |
| Radius: 1.95 mm, Length : 10 mm, |
| Frequency : 1013.7 GHz at the second harmonic, |
| Cavity mode : $TE_{4,12}$, Q-factor : 23720 |
| Operation mode: Complete CW |
| Operating magnetic field: 19.1 T for $TE_{4,12}$ |
| Triode-type electron gun: |
| Cathode radius: 4.5 mm, |
| Maximum cathode current: 1 A, |
| Maximum cathode voltage: 30 kV |
| Gun coil: |
| Maximum input current: 300 A, |
| Maximum magnetic field: 0.183 T |
| Pumping bores: |
| 1.Near the electron gun, |
| 2.Near the output window. |
| Water cooling jackets are installed at a cavity and a collector regions. |

Fig. 6 shows output frequencies as function of magnetic field intensity. Fundamental operations are measured just after the output window and second harmonic operations through high pass filters. Excited cavity modes for almost all radiation peaks are identified.

Fig.5 Photo of Gyrotron FU CW III with a 20 T superconducting magnet

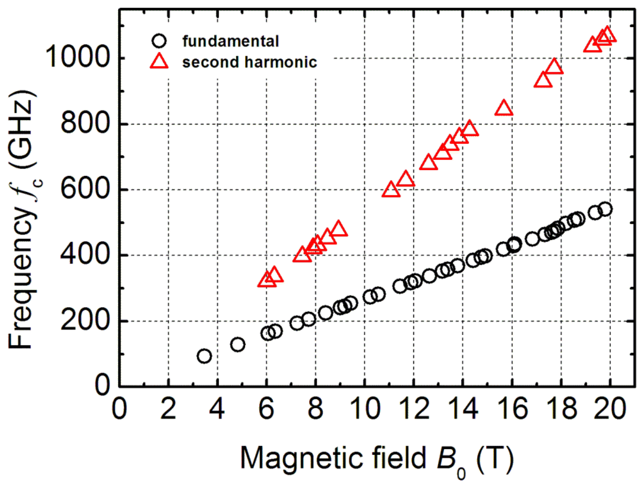


Fig.6 All of the frequencies plotted as functions of magnetic field intensity

The maximum frequencu is 1.08 THz achieved by the second harmonic operation near the field intensity of 20 T. Frequency step tuneability covering the range from 0.1 to 1.08 THz was achieved. The measurement of output power is carried out by a water load. It depends on the cavity modes. Typically, it was several hundred watt at the fundamental operations and several tens watt at the second harmonic operations

## 4. Summary

The first THz gyrotron with a 21.5 T pulse magnet was developed in FIR FU. The gyrotron succeeded in the first experiment on the breakthrough of 1 THz. On the basis of the success, Gyrotron FU CW III was designed and constructed by use of a 20 T superconducting magnet. The cavity with the same dimensions as the pulse gyrotron is installed in Gyrotron FU CW III. Its operation test has already been carried out successfully. Almost all modes operationed in the pulse gyrotroin were excited in the CW modes. The gyrotron will be used for development of high power THz technologies, for example, DNP/NMR spectroscopy, X-ray detected magnetic resonance (XDMR) experiment, accurate measurement of energy levels of positronium, high frequency ESR echo measurement, plasma scattering measurement etc.

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